Rapid ice discharge from southeast Greenland glaciers

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[1] Interferometric synthetic-aperture radar (InSAR) observations of southeast Greenland glaciers acquired by the Earth Remote Sensing Satellites (ERS-1/2) in 1996 were combined with ice sounding radar data collected in the late 1990s to estimate a total discharge of 46 ± 3 km^3 ice per year between 62°N and 66°N, which is significantly lower than a mass input of 29 ± 3 km^3 ice per year calculated from a recent compilation of snow accumulation data. Further north, Helheim Glacier discharges 23 ± 1 km^3/yr vs 30 ± 3 km^3/yr accumulation; Kangerdlugssuaq Glacier discharges 29 ± 2 km^3/yr vs 23 ± 2 km^3/yr; and Daugaard-Jensen Glacier discharges 10.5 ± 0.6 km^3/yr vs 10.5 ± 1 km^3/yr. The mass balance of east Greenland glaciers is therefore dominated by the negative mass balance of southeast Greenland glaciers (−17 ± 4 km^3/yr), equivalent to a sea level rise of 0.04 ± 0.01 mm/yr. Warmer and drier conditions cannot explain the imbalance which we attribute to long-term changes in ice dynamics. *INDEX TERMS:* 0933 Exploration Geophysics: Remote sensing; 1827 Hydrology: Glaciology (1863); 4556 Oceanography: Physical: Sea level variations; 6924 Radio Science: Interferometry; 6969 Radio Science: Remote sensing. **Citation:** Rignot, E., D. Braaten, S. P. Gogineni, W. B. Krabill, and J. R. McConnell (2004), Rapid ice discharge from southeast Greenland glaciers, *Geophys. Res. Lett.*, *31*, L10401, doi:10.1029/2004GL019474.

1. Introduction

[2] Several methods exist to determine the state of mass balance of an ice sheet, and henceforth its present contribution to sea level rise. Here, we address the mass budget method which compares accumulation of snow in the interior with attrition of ice at the ice sheet periphery where it is drained along narrow channels occupied by outlet glaciers [*Weidick*, 1995]. A large number of glaciers were studied in this manner in the north-west, north, and north-east parts of the Greenland ice sheet using satellite radar interferometry data, ice sounding radar data, laser altimetry data, and a radar altimetry-derived elevation model of the ice sheet [*Rignot et al.*, 2001]. Despite residual uncertainties in snow accumulation, it was concluded that this sector of the ice sheet exhibits a slightly negative mass balance. InSAR observations of a systematic retreat of the glacier grounding lines indicate that ice is thinning along the coast, while airborne laser altimetry indicates that the interior regions are broadly in balance with accumulation [*Krabill et al.*, 1999].

[3] Here, we apply a similar approach to the glaciers draining the remainder part of the eastern flank of the ice sheet, south of L. Bistrup Bræ, between 62°N and 72°N. Few reliable glaciological data have been collected in this region prior to the 1990s to estimate ice fluxes [*Olesen and Reeh*, 1969, 1973; *Weidick*, 1995]. Yet, these glaciers should discharge several times more ice into the ocean than all northern Greenland glaciers combined if they are in a state of mass balance [*Reeh*, 1985].

[4] Using differential InSAR, we detect no floating glacier sections south of Størstrommen glacier [*Rignot et al.*, 2001], i.e., the glaciers do not develop floating ice shelves and calve at their junction with the ocean. This is a major physical distinction between northern and southern glaciers [*Reeh et al.*, 1999]. In terms of estimating their ice discharge, this means that ice sounding radar data near the glacier fronts are essential to acquire since no ice thickness proxy can be obtained from ice surface elevation in hydrostatic equilibrium.

2. Data and Methodology

[5] The study region spans from 62°N to 72°N, along the east coast of Greenland (Figure 1). Ice discharge is channelized along narrow, fast moving glaciers due to the presence of a high topographic barrier along the coast. The largest glaciers are Daugaard-Jensen, Kangerdlugssuaq, and Helheim glaciers in the northern part. In the south, numerous glaciers (including Heimdal Glacier), flow rapidly through narrow, deep channels. We name this sector southeast Greenland (SEG) herein.

[6] Drainage basins from these 4 sectors are derived from a digital elevation model of the ice sheet [*Bamber et al.*, 2001], starting from the end points of the flux gates. The total area drained by the 3 large glaciers is 147,000 km^2 (Table 1). The southern sector drains an area 38,280 km^2 in size. Ice caps located between Helheim and Kangerdlugssuaq Glaciers and between Kangerdlugssuaq and Vesfjord Glaciers, which do not drain ice from the ice sheet proper, are not included in this study (Figure 1). Similarly, ice discharge from the glaciers between Kangerdlugssuaq and Daugaard-Jensen glaciers (Vesfjord, Rolige Bræ and Harebræ) is not discussed because it should be small (less than 7 km^3/yr over an area of 21,000 km^2) and we do not have a good combination of velocity and ice sounding radar data in that area.

[7] Ice velocity is measured using InSAR (Interferometric Synthetic Aperture Radar) from the Earth Remote Sensing Satellites, ERS-1/2, collected in late 1995/early 1996, during the tandem mission (one-day time separation pairs), during the winder season (Table 2). InSAR only measures ice motion in the radar looking direction, i.e., a one-dimensional

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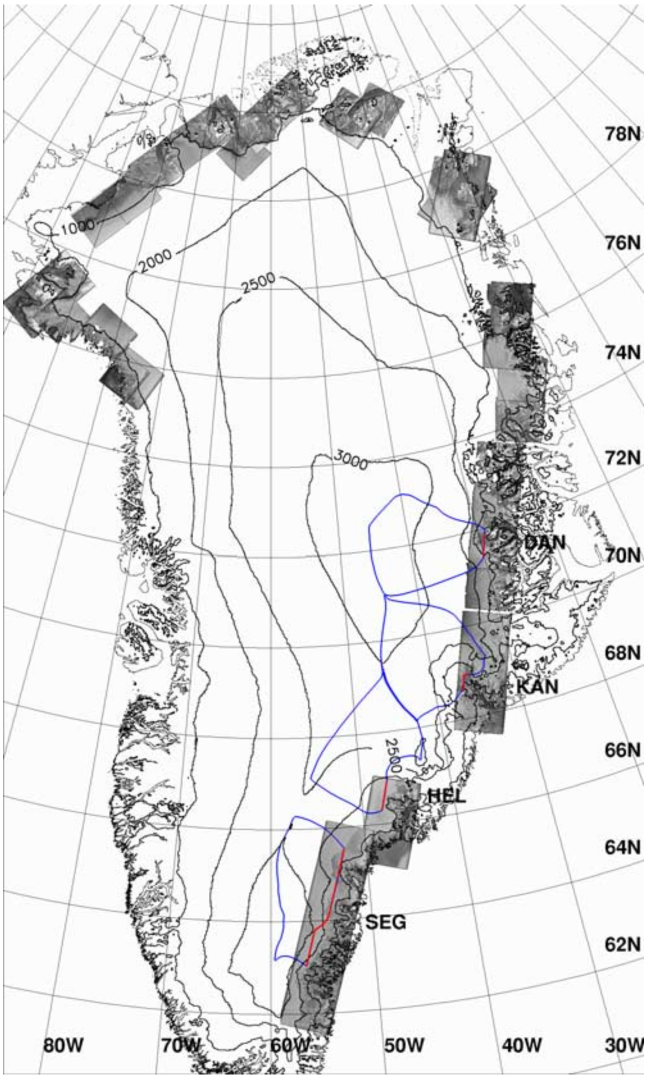

Figure 1. Catchment basin (blue) of 4 glacier areas in east Greenland where glacier discharge was estimated combining InSAR data and ice sounding radar data. The flux gates are shown in red. Elevation contours for 1000, 2000 and 3000 m are shown in black. Radar amplitude images of the ERS-1/2 data used in this study are shown in grey scale (each frame is 120 km × 120 km in size). DAN = Daugaard-Jensen; KAN = Kangerdlugssuaq; HEL = Helheim, and SEG = Southeast Greenland.

component of the velocity vector. No ascending tracks and only descending tracks were available over the study area during that time period. We complemented the InSAR analysis (i.e., phase information in the cross-track direction) of the descending tracks with speckle tracking [*Michel and Rignot*, 1999] in the along-track direction to form velocity vectors assuming ice flows parallel to the ice sheet surface. The precision of velocity mapping is 5 m/yr in the cross-track direction (InSAR analysis) and 50 m/yr in the along-track direction (speckle tracking). Typical flow velocities are greater than 1 km/yr, so that the error in velocity mapping is less than 5 percent, assuming no temporal variability in ice velocity. Only the component of the velocity normal to the flux gate is used in the calculation of fluxes.

Table 1. Ice Flux (Cubic Kilometer of Ice Per Year) vs Balance Flux (Cubic Kilometer of Ice Per Year) of East Greenland Glaciers

Glacier	Ice flux km^3/year	Balance flux (area) km^3/year (km^2)	Mass balance km^3/year
Daugaard-Jensen	10.5 ± 0.6	10.5 ± 1.0 (48,900)	0 ± 1
Kangerdlugssuaq	29.2 ± 1.7	22.9 ± 2.3 (50,950)	−6 ± 3
Helheim	23.4 ± 1.4	30.0 ± 3.0 (47,150)	+7 ± 3
Southeast Greenland	45.7 ± 2.7	29.1 ± 2.9 (38,300)	−17 ± 4
Total	108.8 ± 3.5	92.5 ± 5 (185,300)	−16 ± 6

Area in column 3 gives the size of each catchment basin. Column 4 shows the mass balance, i.e., column 2 minus column 3.

Table 2. ERS-1/2 Orbit Pairs (Two Pairs Per Glacier) Used in the Study and Corresponding Dates of Acquisition of ERS-1 Data (ERS-2 is One Day Later and its Date is Not Shown)

Glacier	ERS-1/ERS-2 Orbits	Dates
Daugaard-Jensen/ Kangerdlugssuaq	23330/3657, 23831/4158	95/12/31, 96/2/4
Helheim	23960/4287, 23459/3786	96/2/13, 96/1/9
Southeast Greenland	22772/3099, 23273/3600	95/11/22, 95/12/27

4. Conclusions

[15] Our mass balance estimates suggest that the glaciers draining southeast Greenland flow faster than required to maintain the ice sheet in a state of mass balance. Surface temperature records of Tasiilq/Ammassalik at (65.6°N, 37.63°W) near Helheim Glacier show a 1.5°C warming for 1885–1935, followed by 1°C cooling for 1935–1985, a 1°C warming for 1985–2000 [*Box*, 2002], and sustained warming from 2001 to present. No long-term (century scale) trend in accumulation is found on the ice sheet at ice core locations, although some areas in the south have pronounced 20–40 year cycles. At ice core D1 (64.5°N, 43.5°W), in southeast Greenland, the mean accumulation is 76.2 ± 17.2 cm water-equivalent per year over 113 years, with a minimum-maximum of 41.3 and 130. There is a slight increase in accumulation of 0.05 cm water-equivalent per year, however not statistically significant due to a high interannual variability.

[16] This leaves warming and changes in ice dynamics as the potential explanation for the observed imbalance. Drops in surface elevation of several meters per year recorded on several east Greenland glaciers cannot be explained by melting alone [*Abdalati et al.*, 2001], and have been attributed to changes in ice dynamics. Such changes may occur as a result of enhanced surface melt water production, which reaches the glacier bed and increases basal lubrication [*Zwally et al.*, 2002]. Enhanced glacier calving may also result from climate warming and accelerate ice flow [*Meier and Post*, 1987]. Calving glaciers are more sensitive to climate change than glaciers ending on land, and once pushed out of equilibrium by climate may continue their retreat even if climate cools down again. Warmer ocean temperature could also exert an important control on calving [*Motyka et al.*, 2003], which remains to be further explored. Enhanced melt water production and warmer ocean during warmer periods earlier this century or possibly in recent years may have triggered the retreat of calving glaciers along the southeast coast. *Weidick* [1995] notes little change in the position of the inland ice since the 1930s in that sector. It will be of interest to examine how the calving glaciers of southeast Greenland will react to the sustained warming trend of the 2000's. In the mid 1990s, the glacier changes were pronounced, widespread, and larger than could be explained from the melting of the snow/ice surface in a warmer climate.